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RESEARCH PAPER

Models of steam-assisted gravity drainage (SAGD) steam chamber expanding velocity in double horizontal wells and its application

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Abstract: The development of steam chamber can be used to evaluate steam-assisted gravity drainage (SAGD) performance. The velocity of steam chamber expanding is the key parameter for evaluating the development of steam chamber. Based on SAGD technology theory and heat transfer theory, two calculation model methods, observation well temperature method and steam chamber edge method for estimating the horizontal expanding velocity of steam chamber, were presented. Through analyzing the monitoring data and numerical simulation results of a typical super heavy oil block developed by SAGD in Fengcheng oilfield in Xinjiang, NW China, the development patterns of steam chamber and temperature variation law in the observation well at different stages are determined. The observed temperature data was used to calculate steam chamber expanding velocity. The calculated chamber velocity at different time was applied to predict the temperature distribution of oil drainage zone at the edge of steam chamber and SAGD oil rate. The results indicate that temperature function of high temperature zone in the observation well temperature curve has a linear relationship with measuring depth. The characteristic section can be used to calculate key parameters such as the angle of the drainage interface, expanding edge and velocity of steam chamber. The field production data verify that the results of the two proposed methods of steam chamber growth are reliable and practical, which can provide theoretical support for the efficient development of SAGD.

Key words: steam-assisted gravity drainage; observation well temperature; steam chamber; steam chamber expanding velocity; oil drainage zone

Introduction

Since the first commercial steam-assisted gravity drainage (SAGD) project, Foster Creek, was put into production in 2001, more than 30 SAGD projects have been implemented in Canada[1–4]. In China, SAGD method was successfully tested in the Liaohe oilfield and Xinjiang oilfield successively in 2005, and soon after it has been commercially applied, with a set of mature industrial developing system established. SAGD is a technique to enhance heavy oil recovery by using steam to deliver heat to the formation, and gravity of the crude oil as driving force[5–7]. During the process, steam injected from the upper well forms a steam chamber, latent heat is released due to condensation on the boundary of the chamber, thus transferring heat to the crude oil and formation around; the condensed water and heated oil flow down to the lower production well due to gravity, as the crude oil around the steam chamber drains out continuously, and the chamber would extend outwards[8–14]. Apparently, study on the key parameters such as the shape and expanding speed of the steam chamber is of great significance for predicting the boundary of the SAGD steam chamber, evaluating the development effect, and guiding production.

Currently, three methods are commonly used to investigate the expanding of the steam chamber: numerical simulation, 4D micro-seismic and observation well analysis. For numerical simulation, the large number of grids in the model often means massive computation, e.g., it is time-consuming to simulate SAGD in FlexWell model with hundred thousands of nodes. 4D micro-seismic method has a low vertical interpretation accuracy, but a relatively high interpretation accuracy for horizontal expansion of the steam chamber. Nevertheless, this method is not widely used because the monitoring interval is

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long at more than one year. The observation well method by placing thermocouple in the well can reflect the real-time expansion of the steam chamber is the major means for personnel on-site to tell the development of steam chamber. Mazdairani et al.[15], Fan et al.[16], Chen et al.[17] established the temperature model of SAGD steam chamber edge based on thermal conduction theory, but did not give an appropriate method to calculate the expansion velocity of the steam chamber. In this work, by using temperature data of observation well, we established two models and corresponding methods to calculate the horizontal expanding velocity of the steam chamber, based on SAGD and thermal conduction, observation well temperature method and steam chamber edge method. With these methods, we can predict the drainage area temperature distribution and the SAGD production.

1. Expanding velocity of the steam chamber

1.1. Basic assumptions

The steam chamber expanding process can be divided into three stages: rising stage (beginning of drainage), lateral expanding stage (peak of drainage), and falling stage (end of drainage when the chamber reaches the boundary of the reservoir or well group)[4, 8–11] (Fig. 1).

We made the following assumptions to study the steam chamber growth laterally along the top of the reservoir: (1) The steam chamber, having reached the top of the reservoir, expands to both sides. (2) The one-dimensional expansion along the normal direction of the steam chamber leading edge is considered. (3) Heat transfers only in the direction perpendicular to the outer edge of the steam chamber, namely, 1D heat transfer. (4) The steam and the cold oil advance in a flat front at constant speed. (5) The heat transfer perpendicular to the outer edge of the steam chamber is considered only, while the convection is not. (6) At a certain time, the system is in a quasi-steady state, i.e., the steam chamber advances at a constant velocity along the normal direction of the edge. (7) Heat loss in the heavy oil flow process is ignored. (8) Thermal conductivity coefficient and reservoir heat capacity do not change with temperature. Based on the assumptions above, the leading edge of the steam chamber can be simplified as shown in Fig. 2. According to the simplified expansion schematic diagram of the steam chamber, the temperature distribution of drainage area at the leading edge can be obtained.

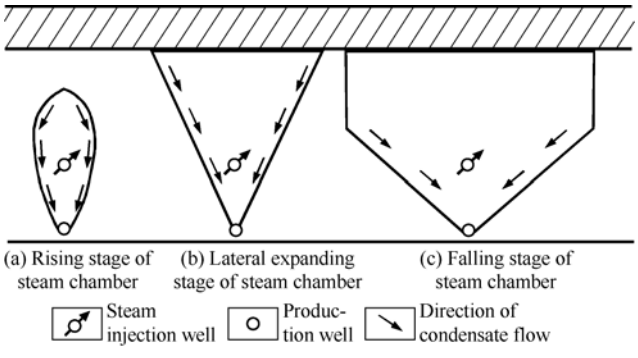
(a) Rising stage of steam chamber
(b) Lateral expanding stage of steam chamber
(c) Falling stage of steam chamber
Steam injection well
Production well
Direction of condensate flow

Fig. 1. Schematic of steam chamber expansion.

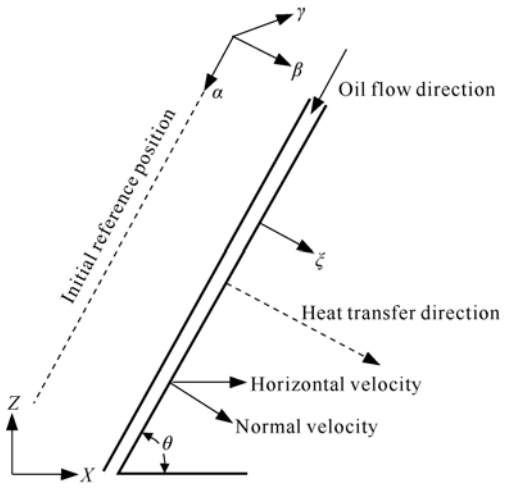

Fig. 2. Schematic of steam chamber expansion.

1.2. Temperature distribution at the edge of the steam chamber

The heat transfer at the leading edge of SAGD steam chamber is at quasi-steady state, and the differential equation of heat conduction can be expressed as[13]:

$$\left[\frac{\partial}{\partial\alpha}\left(K\frac{\partial T}{\partial\alpha}\right)+\frac{\partial}{\partial\beta}\left(K\frac{\partial T}{\partial\beta}\right)+\frac{\partial}{\partial\gamma}\left(K\frac{\partial T}{\partial\gamma}\right)\right]=\rho C\left(\frac{\partial T}{\partial t}\right) \quad (1)$$

where, α represents the tangential direction of the steam chamber interface, β represents the normal direction of the steam chamber interface, and γ is the direction parallel to the axis of the horizontal well. Temperatures in α and γ directions are constant, so Eq. (1) can be simplified as:

$$K\frac{\partial^2 T}{\partial\beta^2}=\rho C\left(\frac{\partial T}{\partial t}\right) \quad (2)$$

To simplify the solution process, variable ξ (apparent distance) is introduced, and the expanding velocity of steam chamber U_ξ is a constant at a given time according to the hypothesis:

$$\xi=\beta-\int_0^t U_\xi \mathrm{d}t=\beta-U_\xi t \quad (3)$$

The partial differential of β in Eq. (2) is replaced by ξ:

$$\frac{\partial^2 T}{\partial\beta^2}=\frac{\partial^2 T}{\partial\xi^2} \quad (4)$$

$$\frac{\partial T}{\partial t}=-U_\xi\frac{\partial T}{\partial\xi} \quad (5)$$

Eqs. (4) and (5) are substituted into Eq. (2), and we can get:

$$K\frac{\partial^2 T}{\partial\xi^2}+U_\xi\rho C\left(\frac{\partial T}{\partial\xi}\right)=0 \quad (6)$$

From Eq. (6) and the boundary conditions:

$$\begin{cases}T(\infty)=T_\mathrm{r}\\ T(0)=T_\mathrm{s}\end{cases} \quad (7)$$

We can obtain the temperature distribution function at the edge of the steam chamber:

$$\xi=\frac{K}{U_\xi\rho C}\ln\frac{T_\mathrm{s}-T_\mathrm{r}}{T-T_\mathrm{r}} \quad (8)$$

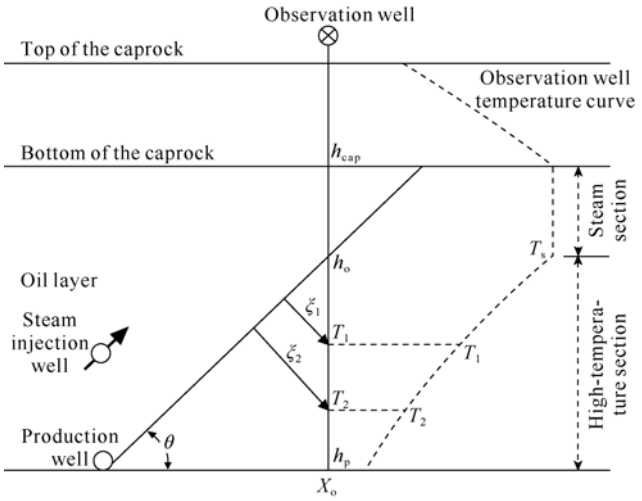

Fig. 3. Schematic diagram of observation well temperature.

1.3. Expanding velocity of steam chamber

From Eq. (8), the expanding velocity of steam chamber can be calculated given the position of the observation well, temperatures of steam chamber and reservoir. In the same observation well, temperatures at different depths of the high-temperature section can be measured, as shown in Fig. 3.

At the same time, correlation between the distance and temperature of drainage interface at the two depths can be expressed as:

$$\begin{cases} \xi_1 = \dfrac{K}{U_\xi \rho C} \ln \dfrac{T_s - T_r}{T_1 - T_r} \\ \xi_2 = \dfrac{K}{U_\xi \rho C} \ln \dfrac{T_s - T_r}{T_2 - T_r} \end{cases} \tag{9}$$

where ξ can be calculated from depth:

$$\begin{cases} \xi_1 = (h_1 - h_o)\cos\theta \\ \xi_2 = (h_2 - h_o)\cos\theta \end{cases} \tag{10}$$

ξ_2 minus ξ_1, and combining Eqs. (9) and (10), we can obtain the simplified equation below:

$$(h_2 - h_1)\cos\theta = \frac{K}{U_\xi \rho C} \ln \frac{T_1 - T_r}{T_2 - T_r} \tag{11}$$

Eq. (11) can be rewritten as:

$$U_\xi = \frac{K}{\rho C (h_2 - h_1)\cos\theta} \ln \frac{T_1 - T_r}{T_2 - T_r} \tag{12}$$

With reservoir position and temperature measured, the expanding velocity of steam chamber can be calculated from Eq. (12).

The heat capacity of the reservoir is related to that of its rock and fluid, and can be calculated from the equation below[18]:

$$M = \rho C = (1-\phi)(\rho C)_r + \phi\left[S_o (\rho C)_o + S_w (\rho C)_w\right] \tag{13}$$

Substituting Eq. (13) into Eq. (12), we can get the horizontal expanding velocity of steam chamber calculated from observation well temperature method:

$$U_{x1} = \frac{U_\xi}{\sin\theta} = \frac{K}{M(h_2 - h_1)\sin\theta\cos\theta} \ln \frac{T_1 - T_r}{T_2 - T_r} \tag{14}$$

2. Expanding pattern and expanding velocity calculation of steam chamber

2.1. Temperature variation of steam chamber in typical observation wells

To study the temperature variation pattern in the typical observation wells and verify the calculation method, we established a SAGD geological model of the horizontal well pair A (parameters shown in Table 1) in Fengcheng block, Xinjiang Oilfield developed by super heavy oil dual horizontal wells with SAGD. To simulate the steam chamber expansion well, the grid was designed at 0.5 m×0.5 m×0.5 m and had 20×201×30 nodes. Considering the uniform expansion of steam chamber along the horizontal well, to reduce the grid number, the length of horizontal section was designed at 10 m, and the vertical spacing between the injection well and the production well was set at 5 m. Therefore, SAGD model of the horizontal well pair was established in CMG-STARS.

The profile of steam chamber expansion over the years is shown in Fig. 4. The steam chamber expands in three stages: rising stage, laterally expanding stage and falling stage. The theoretical model shows that the steam chamber rises to the top of the reservoir one year after the start-up of SAGD. The second to fourth year is the laterally expanding stage of the steam chamber, and it will eventually expand to the pre-set boundary of the reservoir (the junction between SAGD wells).

The inclined drainage interface is not obvious in the rising stage of the steam chamber, and gradually approximates the theoretical one in the lateral expansion stage of the steam chamber (Fig. 4). Temperature of the drainage interface depends on the operating temperature of the steam chamber and the flowability of heated crude oil, which is related to the permeability (vertical and horizontal direction) of the reservoir, viscosity and relative density of crude oil under high temperatures. Usually, draining temperature ranges between 120 and 260 °C. The graph shows that different temperature isolines in the drainage interface are approximately parallel. Moreover, temperature isolines near the production well are sparser than that at the top of the reservoir, which is caused by the long-time heat transfer of thermal fluid between injection and production wells to the nearby formation.

Table 1. Parameters of well pair A in SAGD block.

Parameters	Value	Parameters	Value
Porosity	32%	Formation thickness	15 m
Permeability	2 000×10^{-3} μm^2	Top cap rock thickness	10 m
Oil saturation	75%	Bottom cap rock thickness	5 m
Top buried depth	200 m	Length of horizontal section	400 m
Initial temperature	20 °C	Well spacing	100 m
Reservoir pressure	2 MPa	Vertical distance between two horizontal wells	5 m
Oil viscosity (50 °C)	2×10^4 mPa·s	Operation pressure of the steam chamber	2 MPa

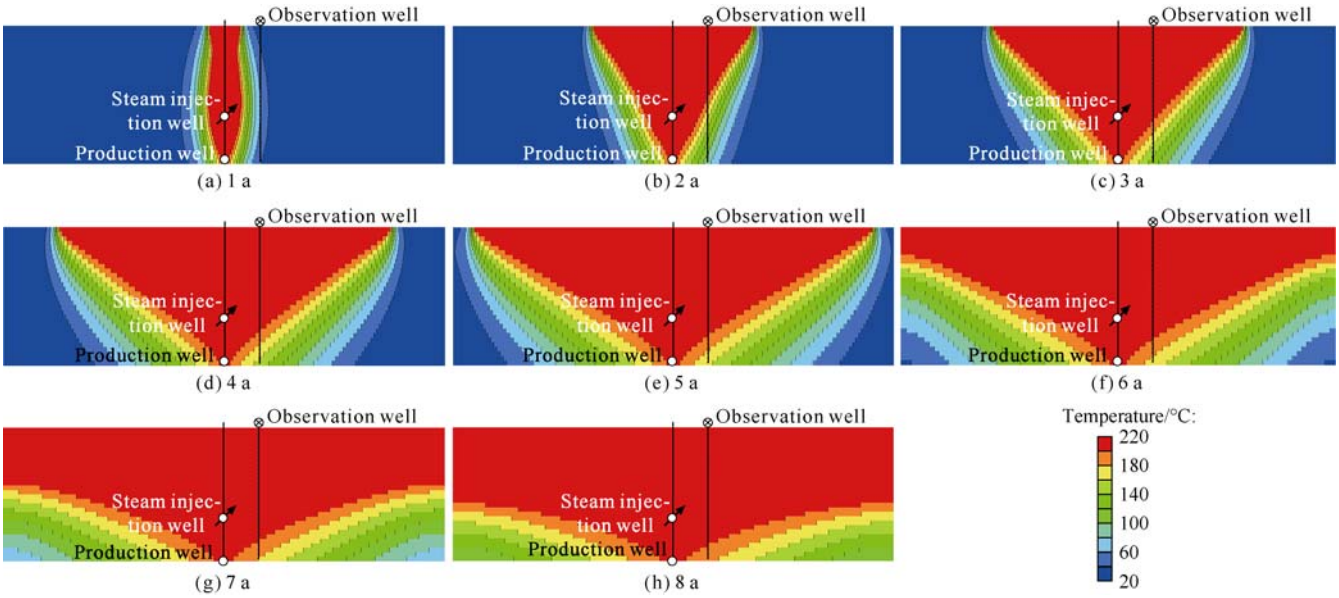

Fig. 4. Profile of steam chamber expanding in typical SAGD well pair.

Eight meters from the SAGD well pair, one observation well was placed to study the temperature variation pattern in it. Fig. 5 shows the temperature curves of the observation well over the years, a typical steam chamber temperature curve has a distinct steam section and a high temperature (80–210 °C) section below it. It enters the production stage when SAGD wells are connected. In the first year, the steam chamber is in the lateral expansion stage. The observation well is close to the steam chamber, so the high temperature section has been observed; as the leading edge of the steam chamber gradually expands to both sides, temperature on top of the observation well rises to 210 °C due to steam heat conduction in the second year. Meanwhile, the leading edge of the steam chamber gradually presents a straight drainage interface, which forms an angle θ with horizontal plane, similar to Butler's hypothesis; θ decreases during the expanding stage of the steam chamber and the falling stage from the 2nd to 6th years.

Temperature variation of well pair A in Zhong 32 block is shown in Fig. 6, which matches well with the simulation result of the typical well pairs. By referring to the straight section of the curve, the expanding speed of steam chamber was calculated and the position of the leading edge was determined.

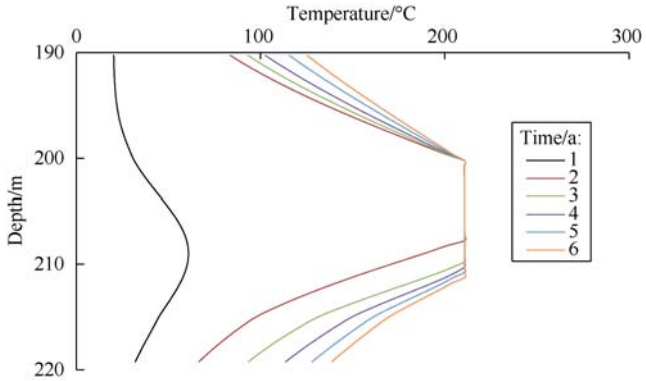

Fig. 5. Temperature curves of the observation well over the years.

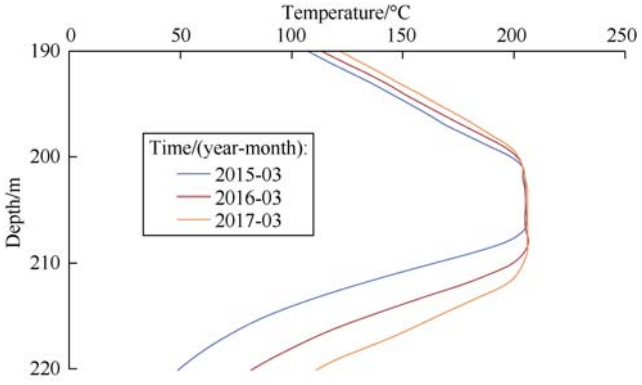

Fig. 6. Temperature curves in observation well of well pair A in Zhong 32 block, Xinjiang oilfield.

2.2. Key parameters to calculate the expanding velocity of steam chamber

2.2.1. Thermal conductivity and thermal capacity of reservoir rocks

Thermal conductivity and thermal capacity of rocks with fluid should be given before calculating the expanding velocity of steam chamber. Properties of the reservoir are shown in Table 2: porosity of 32%, oil saturation of 75%, coefficient of thermal conductivity of 1.73×105 J/(m·d·K). Substituting them into Eq. (13), the thermal capacity of the reservoir calculated was 1.93×10^6 J/(m^3·K).

2.2.2. Drainage area inclination and location of steam chamber leading edge

When the draining temperature at the leading edge of the steam chamber is 200 °C, the pure steam zone with intense

Table 2. Thermal properties of super heavy oil reservoir.

Parameters	Density/(kg·m^{-3})	Specific heat capacity/(J·kg^{-1}·K^{-1})
Sandstone	1 800	960
Super heavy oil	980	1 770
Water	1 000	4 200

heat convection on the drainage area will transform into a high oil saturation zone with heat conduction as the main factor and stable flow of hot fluid. Therefore, the temperature of the drainage area was set at 200 °C. Fitting is needed to determine the position corresponding to 200 °C, because the vertical accuracy of thermocouple temperature measurement is 1 m. When the observation well temperature equals to that of the steam chamber, it indicates that the leading edge of the steam chamber has passed through the observation well, and the parameters of the steam chamber can be calculated with the equations.

To calculate the intersection depth (h_0) between the observation well and the drainage area, the logarithmic term in Eq. (8) was defined as a function of temperature:

$$\psi = \ln\frac{T_1 - T_r}{T_2 - T_r} \tag{15}$$

As shown in Fig. 3, the inclination angle of the drainage area can be expressed as:

$$\theta = \arctan\left(\frac{h_p - h_o}{X_o}\right) \tag{16}$$

Similarly, the horizontal displacement of the steam chamber can be expressed as:

$$s = \frac{h_p - h_{cap}}{\tan\theta} \tag{17}$$

With positions of the leading edge at two different time periods calculated, the expanding velocity of steam chamber can be expressed as:

$$U_{x2} = \frac{s_2 - s_1}{t_2 - t_1} \tag{18}$$

From data collected in 2015, the temperature function in high-temperature zone of observation well presents a linear relationship with depth (Fig.7). According to the temperature function value corresponding to 200 °C, the intersection depth between the observation well and the leading edge of steam chamber is calculated at 207.2 m. The distance between the observation well and the SAGD well group is 8.0 m, and the vertical position of horizontal production well corresponds to the depth of 215 m in the observation well. Then the inclination angle of the drainage area is calculated at 44.27° according to Eq. (16), which is substituted to Eq. (14), and thus the expanding velocity of steam chamber is calculated at 2.04×10^{-2} m/d. The position of the steam chamber at the top of the reservoir can be worked out, given the position of the production well, the inclination angle of the drainage area at the leading edge of the steam chamber, and the depth of the production well. Furthermore, from Eq. (17), the horizontal displacement of steam chamber after two years of production is calculated at 15.4 m.

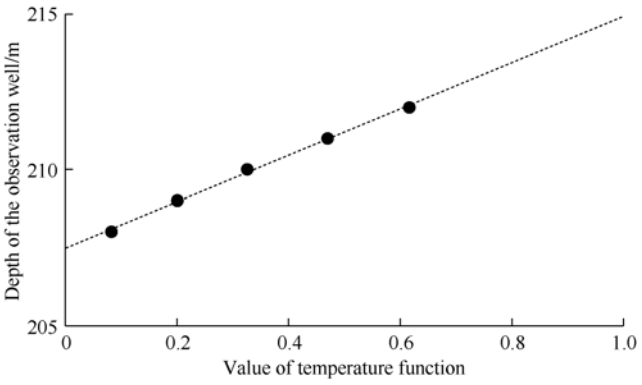

Fig. 7. Temperature function curve of the observation well (2015).

2.3. Comparison of horizontal expansion velocity of steam chamber calculated using two methods

Comparing the position and expanding speed of steam chamber in different periods, it is found that the steam chamber expands faster at the initial stage of SAGD. The horizontal expansion speed of steam chamber slows down as production goes on (Fig. 8). The horizontal expansion speed in 2016 calculated by observation well method (Eq. (14)) is 2.04×10^{-2} m/d, approximate to the average velocity of 2.00×10^{-2} m/d by the leading edge method (Eq. (18)). In actual production, the operating pressure fluctuates quite widely due to on-site adjustment, and the expanding speed of steam chamber is faster under high pressure. On the whole, the expanding velocity calculated by observation well temperature method is different from that calculated by steam chamber edge method. The main reason is that the former is an instantaneous value, which reflects the velocity corresponding to a temperature at a certain time; while the latter is the average value in two adjacent time periods, which is related to monitoring frequency. The two values can verify mutually through comparison.

3. Case study

3.1. Temperature distribution of drainage area

When the steam chamber has not extended to the position of observation well, the leading edge can be predicted from temperature distribution of drainage area, and the width of drainage area can also be predicted. By substituting the calculated expanding velocity of steam chamber and related parameters of well pair A into Eq. (8), temperature distribution of drainage area can be obtained at different time (Fig. 9). As production proceeds, the expanding velocity of steam chamber

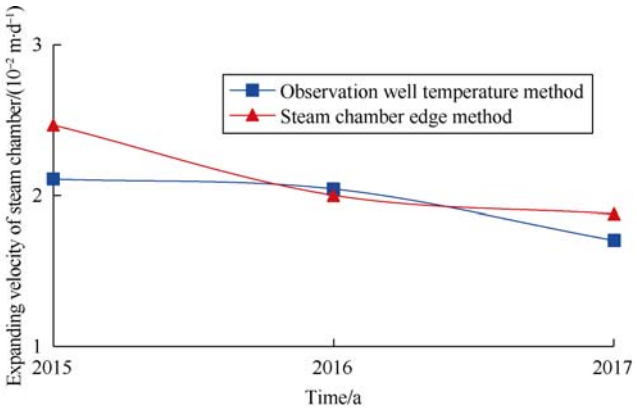

Fig. 8. Comparison of expanding velocity calculation of steam chamber.

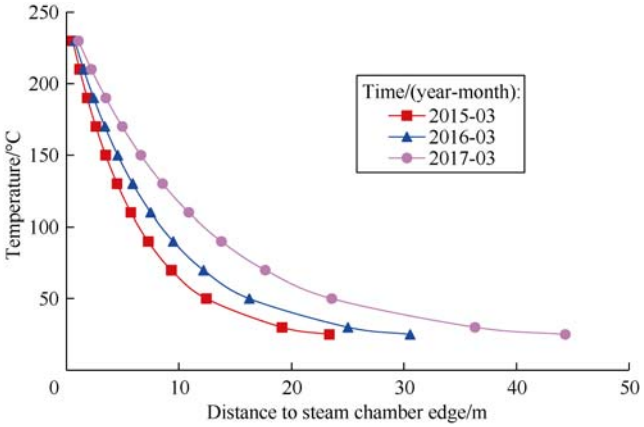

Fig. 9. Temperature distribution of the drainage area.

decreases and the drainage area gradually widens. Quantitative analysis of steam chamber expansion can provide a scientific basis to the selection of production strategies in different production stages.

3.2. Prediction of the steam chamber edge

The position of the steam chamber edge can be calculated more accurately when it passes through the observation well, as shown in Fig. 10. In March 2017, the predicted edge of steam chamber moved horizontally along the X direction to 29.36 m, at an average velocity of 1.7×10^{-2} m/d, and would reach 30.89 m by June 2017, which agrees well with the actual displacement of 31 m, detected via 4D micro-seismic method. At present, researchers in China and abroad tried to enhance oil recovery by drilling vertical wells or infilling horizontal wells in the middle and late stages of SAGD, but SAGD usually adopts high temperature and high pressure production mode, which brings high uncertainty to subsequent safe drilling. In this work, we present two methods to predict the steam chamber expansion, which helps to reduce production risks when making development strategies.

3.3. Production of SAGD based on expanding velocity of the steam chamber

In the traditional Butler's formula during peak production period[2], the production rate is a constant. This simplified method ignores the change of steam chamber expanding speed caused by different working regimes at different time. Substituting the horizontal expansion speed of steam chamber (U_ξ) into the non-traditional Butler's production formula, we can obtain:

$$q=\frac{2K_o g\lambda L\sin\theta}{mv_s U_\xi} \tag{19}$$

And substituting Eq. (14) into Eq. (19), can derive

$$q=\frac{2K_o g\lambda L}{mv_s U_{x1}} \tag{20}$$

According to the expanding speed of steam chamber at different time, corresponding production rates of SAGD can be calculated, which can reflect the change of production in time.

To promote this method, production rate of well A at different time was used to fit Eq. (20), the basic parameters are shown in Table 3. The calculated production rate in April 2015 is 48.07 m^3/d, which fits well with the actual production rate of 47.00 m^3/d (Fig. 11).

It should be noted that, the vertical and horizontal expansion of steam chamber are very uneven due to reservoir heterogeneity and operation factors. The methods to calculate the expanding velocity of steam chamber are only applicable to SAGD well pairs that have high temperature response in observation wells, which reflect steam chamber expansion of nearby SAGD horizontal section.

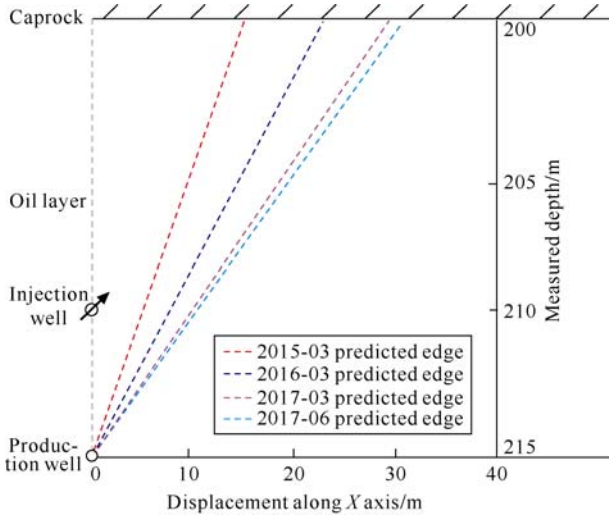

Fig. 10. Position of steam chamber edge at different time.

4. Conclusions

SAGD numerical simulation shows that there is an inclined

Table 3. Parameters for calculating super heavy oil production rate of SAGD.

Parameters	value	Parameters	value
Viscosity-temperature coefficient	4.2	Effective permeability of oil phase	0.4 μm^2
Acceleration of gravity	9.81 m/s^2	Length of horizontal section	400 m
Thermal diffusion coefficient	8.97×10^{-2} m^2/d	Effective horizontal section	350 m
Kinematic viscosity	5.0×10^{-6} m^2/s	Horizontal expansion velocity of steam chamber	2.1×10^{-2} m/d

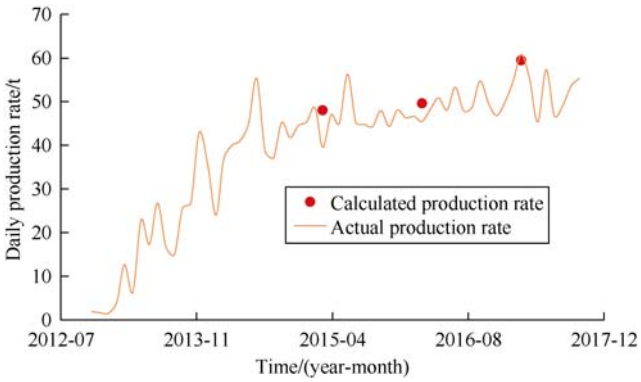

Fig. 11. Comparison of calculated output and actual output of well pair A.

drainage area in the lateral expansion stage of steam chamber, and the temperature function of high temperature zone has a linear relationship with the depth, which lays a foundation for further prediction of the expansion edge of steam chamber and the inclination angle of drainage area, etc.

At different stages of SAGD development, the expanding velocity of steam chamber is different, and expansion speed in the early stage is faster. As production proceeds, the expanding speed of steam chamber slows down. Expanding velocity calculated by two methods, observation well temperature method and steam chamber edge method, agree well with the actual production result.

The formulas for calculating expanding velocity of steam chamber can be used to predict the temperature distribution, leading edge of the steam chamber and production rate at different time of SAGD wells.

Compared with the actual production data of SAGD in Fengcheng Oilfield, Xinjiang, the expanding velocity of steam chamber calculated by observation well temperature method and steam chamber edge method are reliable, which can provide theoretical basis for SAGD application in the oilfield.

Nomenclature

C—specific heat capacity of fluid-saturated sandstone, J/ (kg·K);

g—acceleration of gravity, m/s^2;

h_o—intersection depth between observation well and the leading edge of steam chamber, m;

h_1, h_2—measured depths at two points in the high temperature zone of observation well, m;

h_{cap}—caprock depth, m;

h_p—observation well depth corresponding to the vertical position of horizontal production well, m;

K—heat conductivity of fluid-saturated rock, W/(m·K);

K_o—effective permeability of oil phase, 10^{12} μm^2;

L—effective produced horizontal section length, m;

m—viscosity-temperature coefficient, dimensionless;

M—volumetric heat capacity of fluid-saturated rock, J/(m^3·K);

q—SAGD production rate, m^3/s;

s—horizontal displacement of steam chamber, m;

s_1, s_2—edge position corresponding to t_1, t_2, m;

S_o, S_w—water saturation, oil saturation, %;

t—expanding time of the steam chamber, d;

t_1, t_2—time points corresponding to steam chamber monitoring, s;

T—temperature, K;

T_1, T_2—temperature points in high-temperature zone, K;

T_r—reservoir original temperature, K;

T_s—steam chamber temperature, K;

U_{x1}—horizontal expanding velocity calculated by observation well temperature method, m/s;

U_{x2}—expanding velocity calculated by steam chamber edge method, m/s;

U_ξ—expanding velocity of the steam chamber along ξ direction, m/s;

v_s—kinematic viscosity of crude oil at high temperature, m^2/s;

X—horizontal axis, m;

X_o—distance from observation well to SAGD well group, m;

Z—vertical axis, m;

α—tangential axis of steam chamber interface, m;

β—normal axis of steam chamber interface, m;

γ—axis parallel to horizontal well axis, m;

θ—drainage area inclination angle, (°);

ξ—apparent distance coordinate axis, m;

ξ_1, ξ_2—distance to the drainage area, m;

λ—thermal diffusion coefficient, m^2/d;

ρ—density of fluid-saturated sandstone, kg/m^3;

$(\rho C)_r$, $(\rho C)_o$, $(\rho C)_w$—heat capacity of rock, oil, water, J/(m^3·K);

ϕ—porosity, %;

ψ—temperature function, dimensionless.

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